Environmental Research 163 (2018) 280–288

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Uncontrolled burning of solid waste by households in Mexico is a significant contributor to climate change in the country

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ARTICLE INFO

Keywords:
Open burning of waste
Black carbon emissions
Air pollution
Municipal solid waste
Climate change
Developing countries

ABSTRACT

Uncontrolled burning of municipal solid waste (MSW) is an important source of air pollution and is wide spread in many developing countries, but only limited data quantify the extent of domestic open burning of household waste. Here, we present some of the first field data to be reported on the uncontrolled domestic burning of waste. A representative community of Mexico (Huejutla de Reyes Municipality) was investigated and household surveys, interviews with waste operators and a waste characterisation analysis were completed to assess the extent of, and factors controlling, the open burning of waste. Waste collection provision to rural communities was very limited and, consequently 92% of households in rural areas reported that they disposed of waste by uncontrolled burning in backyards or unofficial dumps. Overall, 24% of the total MSW generated in the Municipality was disposed by uncontrolled burning. Urban and periurban areas received twice-weekly collections and the rate of uncontrolled burning was considerably smaller compared to rural households, corresponding to approximately 2% of total waste generation. Carbon equivalency calculations showed that burning waste in backyards represented approximately 6% of the total and 8.5% of fuel related CO_2Eq emissions by the municipality. Moreover, the equivalent carbon dioxide (CO_2Eq) from black carbon (BC) emitted by uncontrolled burning in backyards was over fifteen times larger compared to methane (CH_4) potentially released from equivalent amounts of combustible biodegradable waste disposal at the official dumpsite. An assessment of local respiratory health data showed the incidence of disease was higher in rural than in urban areas, when the opposite trend is typically observed in the international literature; given the high rate of burning activity found in rural areas we suggest that open burning of waste could be a major reason for the apparent poorer respiratory health status of the rural population and requires further investigation. The results emphasise the importance of including BC from uncontrolled burning of waste in international emission inventories of greenhouse gases and in the assessment of the health status of local communities in developing countries where this practice is prevalent.

1. Introduction

1.1. Background and international context

Solid waste disposal is a worldwide issue and represents a serious risk to public health and the environment. Globally, two billion people lack access to municipal solid waste (MSW) collection services and dispose of household waste typically by open burning, burial or dumping on open ground or into watercourses (UNEP and ISWA, 2015). Providing universal access to adequate, safe and affordable MSW collection services and eliminating uncontrolled dumping and burning of waste are strategic international objectives within the United Nations' Sustainable Development Goals (SDGs) (United Nations, 2015).

Open burning of waste is characteristically a form of low temperature combustion with high contaminant emissions, particularly of black carbon (BC), which contributes significantly to air pollution, causing both health and environmental impacts (US EPA, 2012). There is growing recognition of the significant impact of short lived climate pollutants (SLCPs) on climate change (US EPA, 2012). The MSW sector is a major emitter of two important SLCPs, namely methane (CH_4) and BC. The contribution to global CH_4 emissions from the landfill disposal of biodegradable MSW is well established, however, there is a lack of information relating to MSW as a source of BC emissions (Christian et al., 2010; Stockwell et al., 2016; Wiedinmyer et al., 2014; Yokelson et al., 2011).

Black carbon is a by-product of incomplete combustion that contributes to climate change through direct radiative forcing properties caused by absorption and scattering of sunlight, influencing the properties of clouds and froming deposition on to snow and ice. It is a component of particulate matter (PM) that has a global warming

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https://doi.org/10.1016/j.envres.2018.01.042
Received 30 October 2017; Received in revised form 19 January 2018; Accepted 26 January 2018
Available online 23 February 2018
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potential (GWP) up to 5000 times greater than CO_2 and is the most effective component of atmospheric PM at absorbing solar energy (Bond et al., 2013). There is also a strong link between exposure to BC and potentially severe health effects such as cardiovascular disease, chronic respiratory illness and premature mortality (Janssen et al., 2012; US EPA, 2012). A detailed review of literature on the activity levels and atmospheric emissions from open burning of waste can be found in the Supplementary materials (section S1.1-S1.3).

1.2. Open burning of MSW

Global MSW generation is estimated to be in the region of 1.3–2.4 $\times 10^9$ t y^{-1} (Hoornweg and Bhada-Tata, 2012; Wiedinmyer et al., 2014; UNEP and ISWA, 2015). Wiedinmyer et al. (2014) estimated the total amount of waste burned worldwide assuming a burning activity level for each country, following IPCC Guidelines (IPCC, 2006). This analysis suggested that approximately 0.97 $\times 10^9$ t y^{-1} of total MSW generated globally may be disposed of by uncontrolled burning, comprising 0.62 $\times 10^9$ t y^{-1} by households and 0.35 $\times 10^9$ t y^{-1} by burning at dumpsites (Wiedinmyer et al., 2014). Therefore, approximately 40–50% of total global MSW generation may be disposed of by uncontrolled burning in the open (Christian et al., 2010; Wiedinmyer et al., 2014). This equated to 5% of global annual anthropogenic CO_2 emissions in 2010. Kodros et al. (2016) incorporated health data into the model and estimated that 270,000 premature adult mortalities occurred from chronic respiratory exposure to uncontrolled burning of domestic waste per year. As a comparison, malaria infections are responsible for 580,000 deaths globally each year (UNICEF, 2015). The countries with the highest rates of open burning emissions include: China, India, Brazil, Mexico, Pakistan, and Turkey (Wiedinmyer et al., 2014). Nagpure et al. (2015) reported the street burning of waste in the open in three different areas of Delhi, India was equivalent to 2 – 3% of the total MSW generated. This value was considerably smaller than that suggested by Wiedinmyer et al. (2014), but other important types of open burning, such as in backyards, were not considered and the mass of waste burned was only an approximated estimate and could be subjected to significant error.

1.3. Open burning and MSW management in Mexico

Mexico has one of the largest rates of residential and open dump burning and, therefore, is potentially amongst the main emitters of BC from MSW disposal (Wiedinmyer et al., 2014). According to Wiedinmyer et al. (2014), between 5.0 and 10.0 $\times 10^6$ t y^{-1} of waste (equivalent to 13 – 27% of the total generated) is burned by households and between 10 and 25 $\times 10^6$ t y^{-1} (equivalent to 27 − 96% of the total generated) is burned at dumpsites in Mexico. Earlier estimates (Commoner et al., 2000) suggested that 50% of MSW generated in Mexico was disposed informally in either community dumpsites or by backyard disposal and burning, and the amount of waste burnt in open fires was equivalent to 14.5 $\times 10^6$ t y^{-1}. Further details and discussion of published literature on the open burning waste in Mexico is presented in the Supplementary material sections S1.1-S1.3.

In Mexico, waste generation statistics are calculated by the Ministry of Social Development (SEDESOL) based on the population size and consumption habits following the protocols established in regulation NMX-AA-61–1985 on MSW generation. The amount of waste generated nationally in Mexico in 2010 was over 112,300 t day^{-1}, equivalent to 0.98 kg $capita^{-1}$ day^{-1}. However, waste generation patterns vary greatly between the different states in the country (SEMARNAT, 2013). Overall, approximately 84% of MSW generated in Mexico is collected either through selective or mixed collection system and 10% is recycled or recovered through an industrial process. Nevertheless, up to 12% of the waste generated in Mexico is not accounted for by formal collection and disposal/recovery systems and it is possible that a significant portion of this fraction is disposed by burning in households or in dumpsites (INECC, 2012).

Municipal authorities are required to provide waste management services including waste collection, transport, treatment and confinement, a responsibility devolved to them by the Mexican Constitution as early as 1917 (Poder Legislativo Federal, 1917). Article 100 of the "General Law for the Prevention and Integrated Management of Waste" (Diario Oficial de la Federación, 2003) specifies that the regulations relating to the generation, management and disposal of waste adopted by State Authorities must prohibit the uncontrolled open burning of waste. Therefore, burning of waste is an illegal practice in Mexico.

1.4. Aims and objectives

Little quantitative, experimental evidence is available to validate the published estimates for either the extent of uncontrolled burning of waste or the factors controlling BC emissions from this source, which is highly dependent on the types and composition of waste burnt. This information is necessary to understand the impact of uncontrolled burning of waste on climate change and human health, to improve BC inventories, and provide the sound technical basis to effective policies and practices for MSW management, health provision services and climate change mitigation. For instance, IPCC (2006) guidelines on emissions from the waste sector assume a default value of 0.6 for the fraction of waste burned in open dumps in developing countries. However, there are no experimental data available to substantiate this, and, as a consequence, this emission source is not considered in the IPCC Fourth (Bogner et al., 2007) or Fifth (IPCC, 2014) Assessment Reports.

Therefore, the aim of the research presented in this paper is to quantify the extent of open burning of waste in a representative community of the developing world where this activity is commonly practiced to: (a) improve understanding of the impact of open burning of waste on the environment and public health, and (b) identify policies and practices to mitigate these impacts. A main objective was to develop a waste management profile of open burning of waste in a typical medium-sized community in Mexico to identify the types and quantities of MSW generated and disposed by burning by households.

2. Materials and methods

2.1. Selection and assessment of study area

Federal waste management authorities in the National Institute of Ecology and Climate Change (INECC), State authorities responsible of waste management, and local specialists in the sector were consulted to assist in selecting a representative candidate study area for investigation in Mexico. Small to medium-sized municipalities (population size < 100,000) with unreliable MSW collection services were considered the most likely to dispose of waste by uncontrolled burning in the open, compared to cities with larger population densities where more rigorous waste management controls may be in place (Encarnación-Aguilar, 2015; Solorzano-Ochoa, 2015). Other aspects that were considered in selecting the study area included: transport accessibility from Mexico City, the willingness of local authorities to participate in the project and health and safety conditions in the region. Using these criteria, the Municipality of Huejutla, was selected as the study area for the research.

Huejutla Municipality is located in the state of Hidalgo, in central Mexico. The capital of the municipality is the largest community and most densely populated area of the region and the metropolitan area has a population of over 40,000. Other communities in the municipality are considerably smaller with < 5,000 inhabitants; approximately half of the population live in communities with < 1,500 inhabitants. For this research, households in the study area were sub-divided into three principal categories corresponding to: urban, periurban and rural, depending on the density of the population and the frequency of waste collection services. Households within the urban area were of higher

socioeconomic status compared to the periurban and rural areas (SEDESOL, 2013), and waste collection services to the urban communities operated on a frequent daily or twice per week basis. Interviews with local authorities indicated that approximately 25% of the population in the metropolitan area (equivalent to 8% of the total population of the municipality) were categorised as urban housing and received a daily waste collection service. The periurban community was located between the urban and rural areas and, in this case, waste collections occurred at a reduced frequency of once per week. According to local authority data, 75% of the metropolitan population (equivalent to 24% of the total population) were provided with this level of waste collection service. The rural area was located outside of the metropolitan zone of the municipality and had a lower population density, but larger community size overall (representing 68% of the total population of the municipality). The socioeconomic status of rural homes was generally lower compared to urban or periurban areas of the municipality (INEGI, 2010). Waste collection in rural communities for general household waste was extremely limited and usually these areas were not served by the Municipal Authority.

2.2. Household waste management survey

A door-to-door survey was conducted to determine the waste management practices operating at the household level as well as the drivers influencing waste disposal, recycling and burning patterns in the Huejutla region. Data were collected for a total number of 240 randomly selected properties within the study area including: 100 urban, 80 periurban and 60 rural households. The distribution of households was selected based on the relative densities of the domestic accommodation in each area and the distance from the centre of the municipality. The survey provided information on the general demography of the household members, including gender and age. Information on the feeding of food-waste to pets and domestic animals was also gathered. Other aspects included: waste separation and recycling behaviour, frequency of waste burning activities in the neighbourhood and in the household, identification of other unofficial local sites where open burning of waste was commonly practiced, and the frequency of respiratory diseases in children, adults and the elderly. The surveys were completed between 27 May – 5 June 2015. No significant seasonal variation in waste generation and burning was anticipated, since the monthly average temperatures vary only modestly between the winter and summer periods between 20 − 30 °C.

2.3. Characterisation of waste generated by individual households

Twenty households that frequently burnt waste were identified and selected from those surveyed (5 in each of the urban and periurban areas and 10 in the rural area) for further detailed investigation of household waste composition, to determine the combustible fractions and properties of the waste. Four waste samples were collected from each household over a two-week period (8 − 22 June 2015) for compositional analysis.

The sample size of 20 houses examined in the waste characterisation analysis was relatively small, however, statistical examination of the data was completed to assess the statistical significance of the results. The detailed statistical data are described in the Supplementary information (section S3). Moreover, the waste generation per capita and waste characterisation information recorded were consistent with the neighbouring Municipality of Atlapexco (SanJuan-Marquez and Méndez-Pacheco, 2014).

The analytical procedure was adapted from the Mexican regulation for waste characterisation in households (Diario Oficial de la Federación, 1992) and from UK guidance (WastesWork and AEA, 2010) using whole fresh waste samples. Participants were asked to collect all the household solid waste generated during the assessment period, including waste that they may normally dispose of by uncontrolled burning, and place the material into a polyethylene waste bag that was provided. Waste samples for all 20 households were collected on the same day on two occasions per week (Tuesday and Friday) and were transferred to the nearby municipal dumpsite to complete the composition assessment. The samples were weighed on an electronic platform scale to determine the total mass of waste collected per household. Waste samples were initially processed by passing over a 10 mm screen to separate the fine material fraction (< 10 mm), which was collected and weighed. The main residual portion received preliminary manual sorting into major material categories including: plastics, metals, textiles, glass, paper and cardboard, food and garden waste. The samples were further sub-divided by hand-sorting into 25 separate waste category types, according to their combustible properties (Diario Oficial de la Federación, 1992), and the mass of each waste fraction was measured.

2.4. Interviews with key stakeholders in the waste sector

Information about the generation and management of waste in Huejutla was collected from face-to-face interviews arranged with principal stakeholders engaged in waste collection, recycling or disposal activities within the Municipality. Specifically, interviews were held with the Director of the Ecology Department in the Municipality, the Waste and Cleaning Services Manager, municipal waste truck drivers, waste pickers at the municipal dumpsite, independent waste collectors and managers at waste collection centres. During these interviews, information was gathered about waste management practices, quantities and types of waste collected and recycled and the marketable value of collected recyclable materials. A record of the interviews can be found in the Supplementary material.

2.5. Material flow and statistical analysis

Information obtained from the household surveys, the waste characterisation analysis, and interviews with key stakeholders in the waste sector was used to elaborate a material flow scheme for waste generated, and the different disposal pathways operating in the municipality. The burning frequency in urban and periurban areas was adjusted using a sensitivity analysis to test the impact on the potential amount of waste burned based on different possible collection rates. This provided an integrated overview of the waste mass balance in the region, incorporating waste collection by municipal authorities, recycling rates and waste disposal by householders by alternative means (burning, burial and feeding to animals). This information was statistically scrutinized by analysis of variance (ANOVA) and means comparison tests. The detailed statistical analysis can be found in the Supplementary section (section S3).

2.6. Analysis of respiratory infections in Huejutla

Respiratory health data for Huejutla was obtained from the Municipal Health Authority (Jurisdicción Sanitaria 10 de Huejutla de Reyes, 2015) and the number of cases of respiratory diseases recorded in rural and urban areas was determined.

3. Results and discussion

3.1. Waste management practices in the Municipality of Huejutla

The Waste and Cleaning Services Department of the Municipality operated a waste collection service (the frequency depended on the area served) and one main dumpsite, and all collected waste was disposed at

this site. Waste delivered to the dumpsite is consolidated by a mechanical compacting machine and covered with a layer of soil after material has accumulated for a period of 4–6 weeks. The Municipal Authority ceased burning waste at the dumpsite in 2013 and does not acknowledge the occurrence of informal open-burning by households within the region where it is responsible for the collection and disposal of MSW (as noted earlier, such burning is illegal in Mexico).

The Municipality operated a fleet of 9 trucks (5 compacter trucks, 1 mini compacter and 3 carrier trucks) to collect waste and employed 14 drivers. Truck drivers also engaged in informal recycling activities, which provided an additional income source from the sale of high value recyclates (e.g. aluminium cans, metals, and in some cases polyethylene (PET) and high-density polyethylene (HDPE) containers). Other independent waste collectors (approximately 15 operated in the Municipality) also provided a recyclate collection service (mostly for metals from discarded furniture or appliances) and mainly operated in more densely populated urban areas. Interviews with the group of independent operators suggested that the collection and sale of PET and aluminium cans was common in the Municipality. Twenty informal pickers were licensed by the Municipality to collect waste at the dumpsite for recycling. Recyclable materials collected by these different groups were taken and sold to private recycling transfer centres and five centres were identified in the city that prepared, baled and transported recycled materials for reprocessing. However, no recyclate processing industries operated in the Municipality of Huejutla.

3.2. Waste generation, composition and the extent of open burning

Information obtained from interviews with stakeholders, household surveys, and the waste characterisation assessment was used to calculate:

(1) the amount of waste generated per capita per day;
(2) the proportion of households that burn waste;
(3) the frequency of waste collection services, and
(4) the combustible, non-combustible and food fractions in waste generated by urban, periurban and rural households.

The estimated rate of waste generation per capita was 0.80, 0.69 and 0.43 kg day^{-1} in urban, periurban and rural areas, respectively (Table 1). The results follow the expected pattern associated with the income and socio-economic status of households in these areas, which are greater in urban compared to rural communities (CONAPO, 2013). In Huejutla, burning of waste occurred in 22%, 37% and 92% of households surveyed in urban, periurban and rural areas of the Municipality, respectively. The increase in the rate of households burning waste corresponded strongly with the reduced availability of regular and reliable collection services, as indicated by proxy from the collection service frequency data. However, burning of waste also continued in urban and periurban areas that were served with frequent daily, twice-weekly and weekly collections. A possible explanation why these communities also burned waste was that the collection service was introduced comparatively recently and, although it had operated for approximately three years, the practice of burning waste was a long established and accepted, familiar disposal method. This suggested that other controls, measures, incentives and education strategies are also necessary to change behaviour in the community, in addition to the basic provision of waste collection services. For example, households are not provided with a bin for waste collection, and without a facility to store waste securely between collections, burning may be undertaken as a more convenient means of waste disposal.

In rural areas of Huejutla, 69% of households had access to a waste collection service for bulky and non-compactable materials, such as bed mattresses or glass, but general household waste was not collected. Therefore, the numbers of households burning waste in open fires increased markedly in these areas compared to urban and periurban communities. Thus, the results strongly implicate the lack of frequent and reliable waste collection services as a major reason for the increased rates of open burning of combustible fractions of MSW in developing countries such as Mexico.

3.3. Waste generation per capita in Huejutla compared to other international regions

Fig. 1 compares the per capita waste generation rates estimated for Huejutla with national data for Mexico (INECC, 2012b) and average data for international regions (Hoornweg and Bhada-Tata, 2012). The rate of waste generation per capita is higher in Mexico (0.85 kg day^{-1}) compared to African and South Asian countries, but is less than in other regions of the world. Waste generation per capita in Huejutla (0.64 kg day^{-1}) is also below the national average value for Mexico, and is similar to the average for the African continent, reflecting the predominant rural and socio-economic characteristics of Huejutla Municipality.

3.4. Waste flow analysis

The estimated total rate of MSW generation in Huejutla was 104 t day^{-1} (Table 2). The results showed that the Municipal Authority managed approximately 25% of the household waste generated in the Municipality and a small fraction (2.4%) was recycled informally. A comparison of recycling rates in Huejutla relative to the national

Table 1
Generation rate, general properties, collection and burning of household waste in different socioeconomic community types in Huejutla, Mexico.

Area	Proportion of households that burn waste (%)[a]	Frequency of collection service[b]	Mean (+/- standard deviation)			
			Waste generated (kg $capita^{-1}$ day^{-1})[c]	Combustible fraction (% FW)[c]	Non-combustible fraction (% FW)[c]	Food waste fraction (% FW)[c]
Urban	22	Daily	0.83 (± 0.25)	66.4 (± 0.06)	1.2 (± 0.01)	32.4 (± 0.06)
Periurban	37	Once or twice per week	0.80 (± 0.64)	58.2 (± 0.14)	2.9 (± 0.03)	38.9 (± 0.13)
Rural[d]	92	31% has no service 69% once a month or less	0.43 (± 0.18)	71.7 (± 0.15)	3.8 (± 0.03)	24.5 (± 0.15)
Average	50	–	0.64	65.4	2.6	31.9

FW; fresh weight.
[a] Obtained from household surveys reported here.
[b] Information reported by the Municipal Authority.
[c] Obtained from the waste characterisation analysis reported here.
[d] Waste collection services provided by the Municipal Authority to rural areas is generally only for bulky and non-compactable items and materials including furniture and glass.

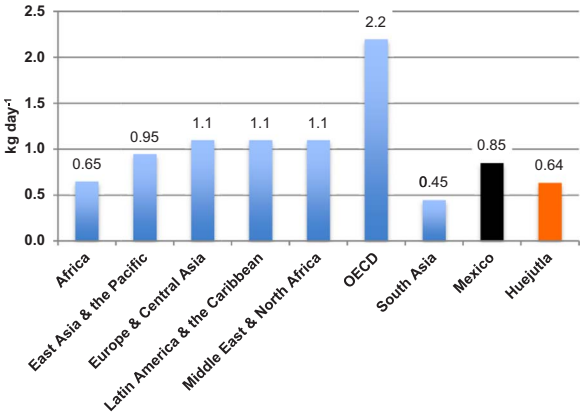

Fig. 1. Comparative data on waste generation per capita (Hoornweg and Bhada-Tata, 2012; INECC, 2012).

statistics for Mexico and to other regions of the world can be found in the Supplementary Information (section S1.4).

Information collected from interviews with stakeholders, household surveys, and the waste characterisation study was integrated to calculate a Material Flow Diagram (MFD) representing the different pathways for recycling and disposal of waste in the Municipality of Huejutla (Fig. 2). The assumptions and calculations applied to develop the MFD are presented in Table 3. The daily municipal waste collection rate was determined from the sum of the commercial and household waste collection data, and was estimated to be approximately 70 t day^{-1} by the Municipal Authority. The data provided by the Municipality regarding household waste collection was verified independently from the survey data and waste characterisation analysis reported here, and was obtained by subtracting the amount of waste that was burned, fed to animals and buried, from the total waste generated by households. This provided a household waste collection rate equivalent to 24.6–25.9 t day^{-1}, which is consistent with the value reported by the Municipality (30 t day). The amount of waste recovered for recycling was based on information obtained from interviews with personnel at the recycling centres in Huejutla. The final disposal rate estimated for Huejutla was obtained by subtracting the waste recovered by recycling centres from the daily household waste collection rate and was equivalent to 64.6–65.9 t day^{-1}.

Sensitivity analysis (Table 3) indicated that 23–25% by weight of the total household waste generated in the Municipality was burned in open fires (Fig. 2), approximately 12% (equivalent to over 30% of the total food waste generated) was fed to animals and 1% was buried. The MFD showed that more than 90% of waste disposal by open burning occurred in rural communities, representing 22.4% of the total MSW generated in Huejutla Municipality. Burning of waste also occurred in urban and periurban areas, but at a significantly reduced rate compared to rural communities, on average representing 4.5% and 9.3% of the waste disposed by burning, respectively, equivalent to up to approximately 2% of the total waste generation overall in the Municipality.

3.5. Estimated emissions from open burning of waste

The total amount of waste burned by households per day in different communities in Huejutla Municipality, based on the gathered field data reported here, was compared to data calculated for the same areas using the assumptions provided by Wiedinmyer et al. (2014) (Table 4). Wiedinmyer et al. (2014) assumed that the extent of open burning of waste per capita in households in Mexico was equivalent to 0.22 kg day^{-1}. Reassuringly, overall activity rates for domestic open burning of waste estimated by direct measurement and from assumed values were generally consistent and were 25.0 (field based mean) and 26.5 × 10^3 t day^{-1}, respectively. We show that more than 20% of the total waste was disposed by open burning by households in a representative community in Mexico (Fig. 2).

The results reported here emphasise the major differences in activity level apparent between different community types in developing countries and the importance of accounting for this to establish accurate activity, and, therefore, BC emission rates from the uncontrolled open burning of waste. Actual estimates of open burning of waste at dumpsites are also required to verify this contribution to the overall extent of the emissions from open burning of municipal waste in developing countries.

Black carbon emissions from open burning of waste by households in Huejutla were calculated by combining the activity levels measured here with available emission factors (EFs) reported in the literature (Stockwell et al., 2016; Wiedinmyer et al., 2014). This showed that the amount of BC emitted was in the range 17.5 – 18.5 t y^{-1} (Table 5) and had a CO_2 equivalent (CO_2Eq) value of approximately 38.6 – 40.6 × 10^3 t y^{-1}, based on an average Global Warming Potential (GWP) for BC of 2200 for a 20-year horizon (Bond et al., 2013; Fuglestvedt et al., 2010). However, published EFs for BC from open burning of waste are based only on a limited number of field measurements and should therefore be interpreted with caution. These values may be improved using EFs relevant to the specific waste characteristics and combustion conditions in the region, and further research as part of this project will be carried out to develop these data.

Particulate matter (PM) emissions from open burning of waste were

Table 2
Municipal solid waste generation and disposal in Huejutla (kg day^{-1}).

Type of household	Population[a]	Household waste generated[b]	Burned[b]	Buried[b]	Fed to animals[b]	Household waste managed by Municipality[c]	Commercial / schools / hospitals[d]	Waste recycled[e]	TOTAL
Urban[f]	10,004	7,972	163–488	0	1,191	6,292–6,618	40,000	2,500	
Periurban[f]	30,011	20,687	929–1,895	0	4,972	13,819–14,786			
Rural	82,890	35,236	23,243	809	6,722	4,463			
Total	**122,905**	**63,894**	**23,263**	**809**	**12,886**	**25,607**	**40,000**	**2,500**	**103,894**
Relative to total waste generated (%)		**61.5**	**22.4**	**2.1**	**12.4**	**24.6**	**38.5**	**2.4**	**100.0**

Notes.
[a] National Census of 2010 (INEGI, 2010).
[b] Obtained from the waste characterisation analysis reported here.
[c] See "Municipal waste collection" in Table 3.
[d] Reported by the Municipal Authority.
[e] Interviews with recycling centres.
[f] Percentages of urban (25% of metropolitan population) and periurban populations (75% of metropolitan population) in the metropolitan area were estimated from information provided by the Municipal Authority.

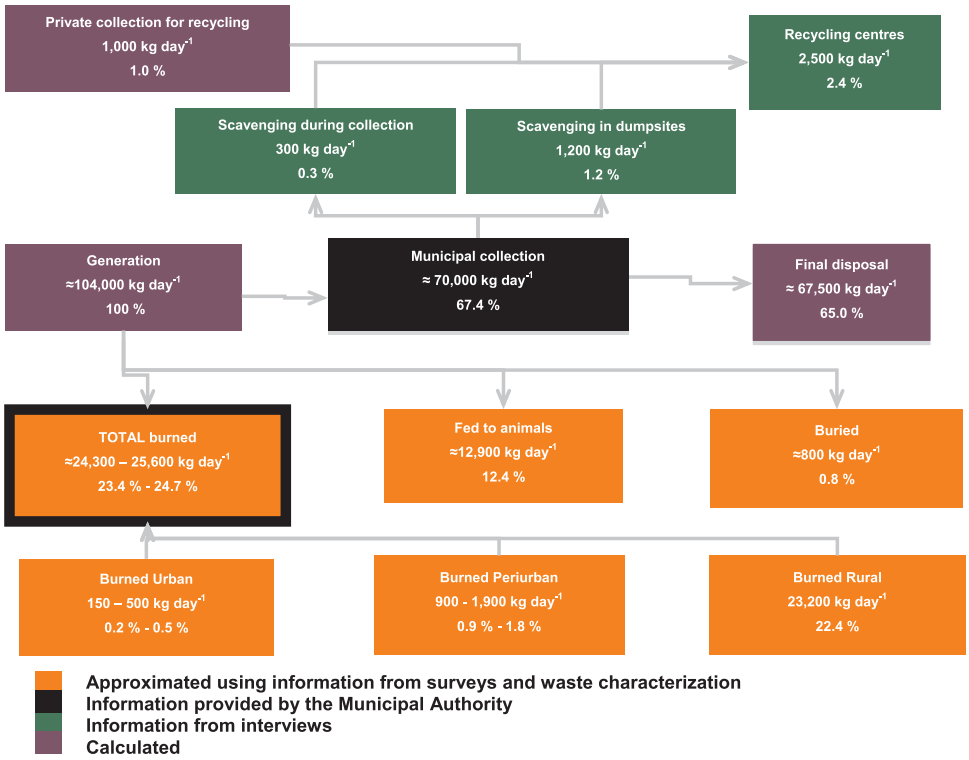

Fig. 2. Waste flow diagram for Huejutla, Hidalgo, México (kg day^{-1} and % of total waste generated).

also calculated and the results were compared to the National Emission Inventory (SEMARNAT, 2009). This showed that PM emissions from open burning of waste represented 6.8 − 7.2% of total PM_{10} and 6.0 − 6.3% of $PM_{2.5}$ emissions in Huejutla based on the 2008 inventory data.

The environmental emissions from burning waste in backyards were compared to other important metrics of atmospheric pollution to illustrate the relative scale and significance of the emissions from uncontrolled open fires. For example, the BC CO_2Eq linked to open burning represented approximately 6% of the total CO_2Eq emissions and 8.5% of emissions related to fuel consumption (Table 5). The BC CO_2Eq was also compared to the production of CH_4 arising from the decomposition of equivalent amounts and types of waste following disposal at the Municipal dumpsite. This analysis used landfill CH_4 EFs for different material types (specifically, cardboard, paper and yard trimming fractions) provided by the Waste Reduction Model (WARM) (US EPA, 2015). The results showed that the CO_2Eq from BC emitted by uncontrolled burning in backyards was more than fifteen times larger (approximately 2,300 t y^{-1}) compared to CH_4 potentially released from the decomposition of equivalent amounts of combustible biodegradable waste deposited at the dumpsite. However, IPCC inventories currently do not incorporate this emission source due to the limited understanding of, and quality of experimental data relating to, the open burning of municipal waste is limited.

3.6. Respiratory disease in Huejutla and surrounding areas

Health records collected from medical centres in the Huejutla district showed that respiratory disease was about twice as frequent in the population in rural compared to urban areas (Fig. 3). This was contrary to the expected trend since respiratory disorders are usually more prevalent in urban communities due to increased exposure to transport and industrial atmospheric pollution emissions compared to rural areas (Jang, 2012; Gartner et al., 2008; O'Reilly et al., 2007; Iversen et al., 2005). Smoking is also a main cause of respiratory disease; however, in Mexico, the frequency of smoking is greater in urban (38.8%) compared to rural (23.7%) populations (CONADIC, 2008) so smoking behaviour cannot account for the reported poorer respiratory health status of rural communities. The medical records indicated the location where treatment was received, but not the origin of patients and, since rural areas have fewer medical facilities, it is likely that the rate of respiratory illness estimated for rural communities may be an underestimate as rural inhabitants often travelled to medical facilities in the urban zone to receive treatment.

Two potential factors could explain the greater incidence of respiratory disease in the rural areas of Huejutla and include emissions from cooking with solid fuels and open burning of waste. Wood is the main cooking fuel in 49.1% of households in Huejutla (INEGI, 2011) and cooking on open fires is practiced to a greater extent in rural areas. However, several studies have also emphasised the potential impact of the open burning of waste is an important contributor to respiratory diseases (Hodzic et al., 2012; Li et al., 2012; US EPA, 2016; Kodros et al., 2016). Whilst the direct impact of burning waste on human health cannot be specifically determined from the collected health data, the results indicated a potential link was apparent between respiratory disease and open burning of waste. Further work is therefore warranted to investigate the implications for human health arising from the open burning of waste by local communities.

4. Conclusions

This research presents the first field results and evidence base on the extent of open burning of household waste by a representative community in a developing country and provides a first step towards the future inclusion of BC emissions from open burning of waste in IPCC emission inventories and estimates. The results showed that approximately 24% of the total waste generated in the study area in the Municipality of Huejutla, Mexico was disposed by open burning by households. The adequacy and frequency of waste collection services was identified as the primary factor controlling the extent of open burning of waste by households. Thus, 90% of the total waste disposed

Table 3
Assumptions and calculations applied to estimate the waste material flow in the Municipality of Huejutla, Mexico.

Waste component	Quantity (t day^{-1})	Explanation of calculation
Total waste generation	104	**Generation = Waste generated in households + Commercial waste** ● **Waste generated in households** was calculated considering the amount of waste generated in households in urban, periurban and rural areas (from the characterisation analysis) and the population in each area: ● **Waste generated in households = Number of households in each area * mean waste generated by household type** ● **Commercial waste:** Information provided by the Municipal Authority.
Municipal waste collection	70	Information provided by the Municipal Authority. The amount of collected household waste was verified using the following calculation based on the survey and waste characterisation data: **Household waste collected = Waste generated in households – (burned waste + waste fed to animals + buried waste)** Together, the estimated amount of collected household and commercial waste was equivalent to 64.6–65.9 t day^{-1}
Final Disposal	67.5	**Final disposal = Municipal waste collection – Recovery from recycling collection centres**
Recovery from recycling collection centres	2.5	Information obtained through interviews with managers at recycling centres.
Scavenging at dumpsites	1.2	Obtained through interviews with waste pickers at dumpsites.
Scavenging during collection	0.3	Obtained through interviews with municipal waste truck drivers and their assistants.
Private collection for recycling	1.0	Obtained through interviews with independent waste truck drivers and their assistants collecting recyclable materials.
Waste burned	24.3–25.6	**Waste burned = Households that burn waste * combustible waste * estimated burning frequency** ● The proportion (%) of **households that burn waste** was obtained from the surveys in the different areas and was estimated as 22, 37 and 92% of households in urban, periurban and rural areas, respectively. ● The amount of **combustible waste** was estimated using information from the waste characterisation analysis. ● The **burning frequency** in urban and periurban areas was adjusted in a sensitivity analysis to test the impact on the potential amount of waste burned. This was carried out by assuming the frequency of burning waste varied between one to three days per week, respectively, in urban and periurban areas, where waste collection services are provided once or twice per week. Rural households were assumed to burn waste daily, since they do not receive a waste collection service, or waste is collected infrequently at a rate of once per month or every three months. Waste collection services provided by the Municipal Authority to rural areas is generally only for bulky and non-compactable items and materials including furniture and glass.
Waste fed to animals	12.9	**Waste fed to animals = Households with animals fed with food waste * food waste** ● The number of households with **animals fed with food waste** was calculated using the information from the survey. ● **Food waste** was estimated from the waste characterisation analysis.
Waste buried	0.8	**Waste buried = Houses that bury waste * non-combustible waste** ● Houses that bury waste were considered to be 60% of the rural households: o 31% of the rural population had no collection service and therefore buried all their non-combustible waste; o 29% of rural households had a waste collection service, but also buried all their non-combustible waste because the frequency was once a month or less and general household waste was not collected (only bulky items such as tyres, bed mattresses, etc. were collected). ● **Non-combustible waste** was estimated from the waste characterisation analysis.

Table 4
Comparison of total household burning of waste in the Municipality of Huejutla, Mexico based on field measurements compared to assumed values.

Type of household	Field based data (kg day^{-1})	Data calculated using theoretical assumption[a] (kg day^{-1})
Urban	163 – 488	2,159
Periurban	929 – 1,895	6,478
Rural	23,243	17,892
Total	**24,334 – 25,627**	**26,529**

[a] See (Wiedinmyer et al., 2014).

by open burning was in rural areas that did not receive a household waste collection service by the Municipal Authority. Regular waste collections operated in urban and periurban areas, however, households in these zones were not provided with a receptacle for the waste and they also burned waste equivalent to 2% of the total waste generated and approximately 10% of the fraction disposed by burning. Therefore, in addition to providing regular waste collections, further support may be necessary to eradicate open burning completely, such as education programmes and providing households with a secure means of storing waste between collections.

A comparison of local respiratory health data showed that the incidence of disease was increased in rural areas where the rate of open burning waste was greatest compared to urban areas. The specific cause of the increased incidence of respiratory illness was not specifically identified, but open burning of waste in rural areas may be a strong plausible explanation requiring further investigation, in addition to the common practice of cooking on open solid fuel fires. Reducing the burden of health care potentially associated with open burning of waste in developing countries could justify investment in providing greater access to more effective waste collection services and particularly to rural communities where uncontrolled burning of waste is widely practiced. Further epidemiological research is needed to quantify the link between the open burning of waste and respiratory health particularly focussing on rural populations in developing countries where this method of waste disposal is widely practiced.

Burning activity rates by households obtained from this research were combined with existing literature values for atmospheric EFs and showed that the BC CO_2Eq from domestic open burning represented 6% of the total CO_2Eq emissions and 8.5% of emissions related to fuel consumption for the community of Huejutla. Also, BC CO_2Eq from uncontrolled burning in backyards was fifteen times larger compared to CH_4 released from the decomposition of equivalent amounts of combustible biodegradable waste disposed at a final disposal site. This information suggests that action is needed to reduce domestic open burning of waste and that this would have a significant impact on improving air quality and respiratory health, and, reducing climate change. Open burning of waste at dumpsites is also a significant atmospheric emission source, but the burning of waste by households using open fires may be more challenging to control.

Table 5
Estimated emissions from domestic open burning of waste in Huejutla de Reyes and relative to total and fuel emissions of CO_2 equivalents.

	Waste burned ($t\,y^{-1}$)	[a] Emission Factors ($kg\,t^{-1}$)**			Emissions ($t\,y^{-1}$)				Emissions per capita ($kg\,y^{-1}$)	[b] % of CO_2Eq	
		[c] BC	[d] PM_{10}	[e] $PM_{2.5}$	BC	[f] BC (CO_2Eq)	PM_{10}	$PM_{2.5}$	[f] BC (CO_2Eq)	Relative to total emissions	Relative to emissions from fuel
[g] Low Estimate	8,882	1.97	11.9	9.8	17.5	38,553	105.7	87.0	313.7	5.6%	8.3%
[g] High Estimate	9,354				18.5	40,601	111.3	91.7	330.3	5.9%	8.7%

[a] Emission Factors are displayed in $kg\,t^{-1}$ of waste burned.
[b] Total emissions per capita were 5.62 t CO_2Eq and 3.8 t CO_2Eq for fuel use (e.g. transport, industrial, power generation and domestic) in Mexico in 2013 (INECC and SEMARNAT, 2015).
[c] Average BC EF (Christian et al., 2010; Stockwell et al., 2016).
[d] Woodall et al. (2012).
[e] Average $PM_{2.5}$ EF (US EPA, 1995; Lemieux et al., 2000; Christian et al., 2010).
[f] Average BC CO_2Eq for open biomass burning in a 20 year horizon is 2200 (Bond et al., 2013; Fuglestvedt et al., 2010).
[g] High and low estimates were calculated using a sensitivity analysis described in Table 3.

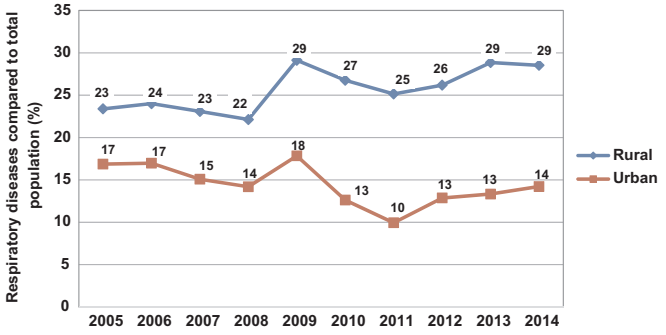

Fig. 3. Respiratory disease in the total population in Huejutla and surrounding area (Jurisdicción Sanitaria 10 de Huejutla de Reyes, 2015).

Acknowledgements

Natalia Reyna is funded by a PhD studentship supported by the National Council of Science and Technology, Mexico (381396) (CONACYT); the Secretariat of Public Education, Mexico (BC-2495) (SEP); the Department of Civil and Environmental Engineering, Imperial College London; the Worshipful Company of Paviors also assisted with travel costs to support the fieldwork.

We also thank all the individuals who provided help, assistance, data and insight, including local authorities in Huejutla Municipality; plus informal sector workers and city residents of Huejutla. The views expressed here are those of the authors alone.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.envres.2018.01.042.

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